The L1551NE Molecular Outflow

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ABSTRACT

L1551NE is a very young protostar (Class I or perhaps Class O), located very close to L1551-IRS5. It is the second brightest far-infrared source in the Taurus molecular cloud complex, but its proximity to the brightest source IRS5 has prevented effective observations of any molecular outflow. We here present evidence that it does indeed possess an outflow, that the optical/infrared reflection nebula is associated with the blue-shifted outflow lobe, and that the L1551W outflow does not originate from L1551NE as has been suggested.

1. Introduction

Low-mass protostars and young stellar objects can be classified according to their near-to far-infrared properties as Class I, 11, or 111 (Lada 1987). Class 1 sources have rising spectral energy distributions (SEDs) between 2 and $25\mu m$, Class 11 have substantial infrared excesses but slowly falling SEDs longward of $2\mu m$, and Class III are nearly stellar in their SEDs. These differences are believed to reflect their evolutionary status, ranging from the young Class 1 which are embedded stars cocooned by a dust envelope, through Class 111 which are optically visible and have little obscuring dust.

More recently a fourth class has been suggested, Class O, whose sources have steeply rising SEDs in the mid- to far-infrared, and which are not visible at wavelengths shorter than $\sim 10\mu m$. These are believed to be the youngest protostellar objects, where the bulk of the fills] mass has not yet finished accreting onto the protostar (André, Ward-Thompson & Barsony 1 993).' Few Class O sources are yet known. Barsony (19!)-1) lists fourteen, including B335, VLA1 623, and L] 527 among the better known (Eiroa et al 1994). A study of Class O sources can reveal conditions in the cloud just after the initial collapse of the core.

L1551NE (131950 $4^h28^m50.5^s + 18°02'10''$ (Draper, Warren-Smith & Scarrott 1985)) is a young stellar object in the 1,1551 molecular cloud, at a distance of 160 pc (Snell 1981). Discovered by Emerson et al (1 984) from IRAS data, it is the second brightest embedded source in the Taurus complex, with $L_{bol} \sim 6L_\odot$ (Emerson et al 1984). (1.1551 -11{S5 is the brightest, at $L_{bol} \sim 28L_\odot$ (Butner et al 1991)). The $25/60\mu m$ colour of L1551 NE is very red, implying that it is younger than T Tauri stars (Tamura et al 1991; Moriarty-Schieven et al 1994), and is very heavily embedded. Despite its relatively large luminosity it was only barely detectable by IRAS at 12pm, and is extended compared to point sources at 2.2 μm (from K-band images presented by Hodapp (1994)). The radial density distribution of 1,1551NI! has been modelled by Barsony & Chandler (1993) from $800\mu m$ images, and by Butner et al (1 994) from 1 00μm and 200μm observations. Both found that the density distribution was much shallower than the $n(r) \sim r^{-1.5}$ predicted by the "in side-out" collapse model of Terebey, Shu & Cassen (19S4). This shallow distribution is similar to Class O sources like L1527 (Butner et al 1994) and VLA 1623 (André et al 1993). These similarities to Class O objects suggest that, rather than a traditional Class I object (Barsony & Chandler 1993), L1551NE may be either Class O or a transition stage between the two classes.

Whatever its classification, L1551NE is an important object to study because of its proximity and luminosity. It is also important to know what other aspects of the star formation process 1,1551 NE exhibits. For example, does 1,1551 NE possess a molecular outflow? As yet, only circumstantial evidence for an outflow has been presented. A cometary reflection nebula was identified by Draper, Warren-Smith & Scarrott (1985), whose polarization vectors imply reflection of a source at the position of L1551NE, located at the apex of the nebula (see Figure 1). Such cometary nebulae are frequently associated with molecular outflows (Tamura et al 1991; Moriarty-Schieven et al 1992; Hodapp 1994). Two Herbig-Haro objects, which arc usually assoc iated with higll-speed protostellar jets, have been attributed to 1,1551NlI; (Graham & Heyer 1990). Finally, 1,1551 NE has been suggested as the origin of the 1,1551 W outflow (Moriarty-Schieven & Wannier 1991; Pound & Bally 1991).

The extreme proximity of 1,1551 NE to the much brighter, better studied, and better known 1,1551 -11{,S5 (a mere 0.4' south and 2,4' west of L1551NE) places it within the red-shifted outflow lobe of the 1 RS5 outflow (Figure 1). This has prevented a positive identification of a molecular outflow to date. Moriarty- Schieven et al (1 992) have found that searches using CO J =3-2 emission are far more suc cessful at finding outflows than those using CO J=1 -O, either because of the smaller beamsize of the higher frequency observations aud consequent less beam dilution, or because the warm and perhaps optically thin emission in the wind is more intense at the higher transition making ident ification easier. For this reason, wc choose to map the CO 3-2 emission in the vicinity of 1,1 551NE. We report below direct evidence for a molecular outflow from 1,1551N11.

2. Observations

The observations described in this note were obtained 5 September 1994 at the James Clerk Maxwell Telescope (J CMT)[2], which was equipped with a 300-3S0 GHz cooled S1S receiver, tuned to 345.796 GHz in the upper sideband. The beamsize (FWHM) is ~14". The backend was the DAS digital autocorrelator spectrometer operating at 250 MHz bandwidth, with channel spacing of 156 kHz, or 1S9 kHz resolution (0.16 km S-l).

Focus was checked at intervals throughout the night, and pointing was checked on],1 551-IRS5 immediately before and after mapmaking. The telescope output was calibrated to the T_A^* temperature scale using both a hot (ambient temperature) and cold load. The typical system temperature encountered was ~1 500 K (double sideband). We integrated for 720 seconds (on+ref) at the central position of 1,15fjl NE, and for 120 seconds for all other points, using a reference position located S00" cast and 800" south of L1551NE (placing it outside of the 1,1551 molecular cloud (Moriarty -Schieven & Snell 19S8)). Spectra in the map were spaced every 15".

A single spectrum of CO J=3-2 was obtained toward IRC+1 0216, in order to compare with "standard" archival spectra to correct to a standard JCMT T_A^* temperature scale. The assumed integrated intensity (over the interval -50 to +5 km s^{-1}) was $\int T_A^*$ = 407 K km s^{-1}. The data were multiplied by this correction factor. All displayed maps and spectra usc this normalized temperature scale. A. further correction for the main beam efficiency ($\eta_{mb}=$

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[2]The JCMT is operated by the Royal Observatory Edinburgh on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organization for Scientific Research, and the National Research Council of Canada.

0.53) (Matthews 1993) was applied when calculating mass, energetics, etc.

3. The Data

Figure 2 is a map showing the CO J=3-2 spectra, which have been smoothed to 0.54 kill S-1 resolution. The (0,0) position is located toward 1,1531 N E. Although all spectra show rwd-shifted line wings, it is apparent that the line wings are broadest and most symmetric toward the (0,0) position, implying that this is the origin of an outflow.

Figure 3 shows channel maps of red- and blue-shifted emission in 0.5 km s^{-1} intervals centered at 4.5 to 1.0 km s^{-1} (above) and 10.0 to 15.5 km s^{-1} (below). (The velocity interval 5.0 through 9.5 km s^{-1} has been omitted because of possible confusion from self-absorption as well as from the IRS5 outflow.) The blue-shifted emission lobe is centered on 1,1551 N E, and extends westward. Red-shifted emission appear-s to extend both west and cast of 1,1551 Nit. It is clear from this figure that the blue-shifted lobe is associated with L1551NE, but the red-shifted emission is more confusing. A comparison with the CO J=1-0 maps from Moriarty y-Schieven & Snell (1988) shows no emission at velocities blue-ward of ~4 km s^{-1} in the neighbourhood of 1,1551NE, but reveals that L1551NE is just within the edge of a region of bright red-shifted emission. Emission from the IRS5 outflow is thus confusing the r-cd-shifted emission shown in Figure 3, but the peak within 1() "-20" of L] 551 NE suggests that some of the red-shifted emission arises from an outflow associated with 1,1551NE.

Another feature visible in Fig. 2 is narrow (~1 km s-1 width) self-absorption seen toward most spectra, but which is most prominent towards 1,1,551 NE and north-west. This self-absorption is most likely clue to an extended envelope of cold gas surrounding L1551NE and is perhaps the signature of the cloud core from which L1551NE formed. If so this establishes the velocity of L1551NE (after subtracting a 2-component gaussian model of the emission line and finding the centroid velocity of the absorption feature) as V_{LSR} = 6.9S ± 0.05 km s^{-1}.

(The ambient velocity in the vicinity of IRS5 is V_{LSR} = 6.7 ± 0.1 km s-' (Moriarty-Schieven & Snell 1988), which is a 2-3σ difference.)

4. Mass and Energetic

We can estimate the mass of molecular gas involved in the 1,15,71NE outflow, If we assume LTE, then the column density of CO can be written

$$N_{CO} = \frac{4.7 \times 10^{12} T_{ex}}{e^{-\frac{33}{T_{ex}}}} \int T_R dv$$

where T_{ex} is the excitation temperature of CO, and $\int T_R dv$ is the integrated intensity over some velocity interval. To calculate mass, we further assume optically thin emission, N_{H_2} = 1.25 x $10^4 N_{CO}$, d=160pc, and T_{ex}=25K (the mass estimate varies by less than a factor of two over a temperature range of 15-401<).

Mass estimates are shown in Table 1. Also shown are estimates for the momentum and kinetic energy of the lobes, summed over individual velocity increments over the red- anti blue-shifted lobes. Velocities have not been corrected for the inclination of the outflow from the line-of-sight.

We can estimate the dynamical age (τ_{dyn}) of the outflow from its extent and the maximum velocity seen. From Fig. 2, each lobe appears to extend ~20" (0.016 pc) from the center. The maximum velocity seen in both the reel and blue wings of the central position (Fig. 1) is $\sim \pm 10$ km s^{-1}. This yields $\tau_{dyn} \sim 2000$ yr, implying a mechanical luminosity of the! outflow $L_{mech} \sim 0.05 L_{\odot}$,

The correction for outflow inclination, it must be noted, may be large. If the inclination angle i is defined as the angle between the outflow axis and the line-of-sight, then the momentum and kinetic energy must be corrected by ($\cos i)^{-1}$ and $(\cos i)^{-2}$ respectively, while the dynamical age and mechanical luminosity go as $\cos i / \sin i$ and $\sin i/(\cos i)^{-3}$.

5. Discussion

The blue-slliftml outflow lobe extends nearly eastward from 1,1551 NE, and though the red-shifted lobe is somewhat confused by emission from the IRS5 outflow, it too is oriented east-west and wc infer that the red lobe extends westward. The orient, tion of the L1551NE molecular outflow is thus nearly east-west, roughly perpendicular to tile protostellar envelope as traced by tile $800\mu m$ dust continuum map of Barsony & Chandler (1993). The blue-shifted outflow lobe is coincident with the optical/infrared reflection nebula (Draper et al. 19S5; Hodapp 1994), as one would expect from reflection of protostar light off the walls of a cavity hollowed out by an outflow. The blue lobe appears to extend less than 30" in Fig. 3, but the reflection nebula extends ~1' from L] 551NE. It is likely that the outflow extends at least as far as the end of the cavity delineated by the reflection nebula, but the emission must be weak. It is thus possible that we have missed a significant fraction of the blue-shifted gas, perhaps underestimating the mass by a factor of as much as 2 (and the dynamical age by a similar factor). The red lobe may also extend further than we have mapped, although we are mom likely to have overestimated the mass because of confusion with the 1 RS5 outflow.

The L1 551 NE molecular outflow is smaller, and has less kinetic energy and momentum (by a factor of ~10) than any of the outflows listed by Fukui et al (1993). (It is unlikely that their survey would have detected it even if it hadn't been so close to IRS5.) This is, however, most likely due to its young dynamical age (~2000 yr). The implied mechanical luminosity (0.05 $L_\odot$) lies well within the range listed by Fukui et al (1993), and indeed its ratio of outflow mechanical luminosity to source bolometric luminosity (L_{mech}/L_{bol} = 0.05/6 = 0,00S) is nearly identical to that of the IRS5 outflow (L_{mech}/L_{bol} = 0.3/2S = 0.01 (Moriarty-Schieven & Snell 198S; Butner et al 1991)).

Graham & Heyer (1990) have attributed two HH objects, located 5' to 6' to the north-east, to 1,1551 NE. Though the full extent of the rml-shifted lobe is uncertain, it is unlikely to extend as far as the HH objects.

Finally, L1551NE has been suggested as the origin for t he 1,1551 W flow (Moriarty - Schieven & Wannier 1991; Pound & Dally 1991), a nai row, well-collimated red-shifted outflow lobe extending more than 20' west of 1,1551NI; or 1 RS5 (Figure 1). We now see, however, that the blue lobe extends west from L1551NE, so that it cannot be the origin of the 1,1551117 outflow. It is interesting then to speculate on the oi igin of the 1,1551 W outflow. Pound & Bally (] 991) have speculated that the western extension of the lobe is unrelated to tile part which overlaps the IRS5 blue lobe, and that the origin may be a 100μm point source IRAS 04278+1758 (see Figure 1). The remarkable colineai ity of the cast and west sections of the 1,1551 W lobe, and the >3' offset of the source from the lobe, argue against this scenario, however. Unless there is some very heavily embedded, as yet undetected Class O source creating the outflow, and the relatively large dynamical age of the outflow ($\sim$6 x 10^5 yr) argues against this as well, the only remaining outflow source is IRS5 itself. The L] 551 W outflow may represent a previous outflow stage of 11{.S5, i .c. a "fossil" outflow as suggested by Moriarty-Schieven & Wannier (1991).

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q'able 1. Mass and Energetics

	Red Lobe	Blue Lobe	Total
Mass ($M_\odot$)	0.0058	0.()()1 1	0.0069
Momentum ($M_\odot$ km s--1)	0.026	0.00'1	0.030
Kinetic Energy (erg)	1.3 X1042	0.2×10^{42}	1.5×10^{42}
Mechanical Luminosity ($L_\odot$)			0.05

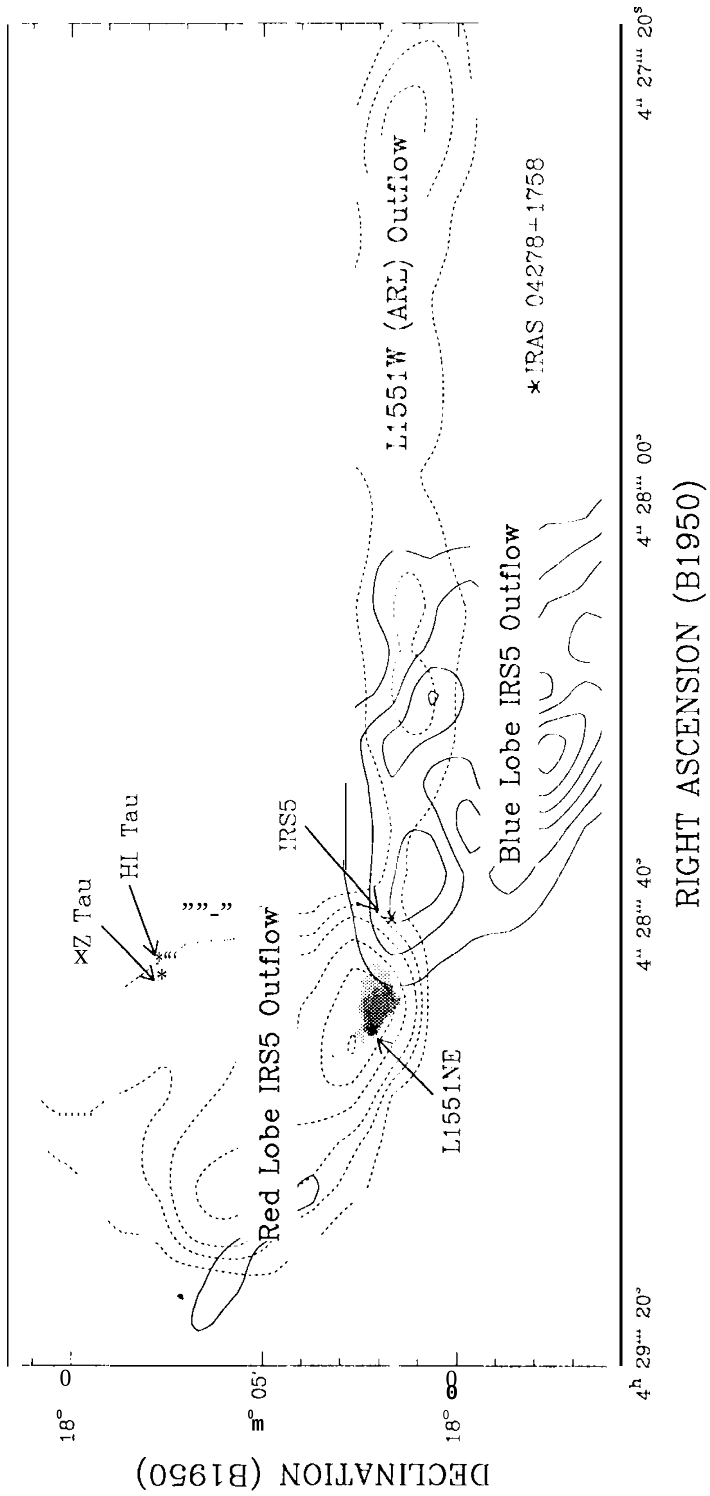

Fig. 1.- Figure showing the locations of various features in the area of L1551NE. The black "star" and gray shading indicate the position of L1551NE and its associated reflection nebula.

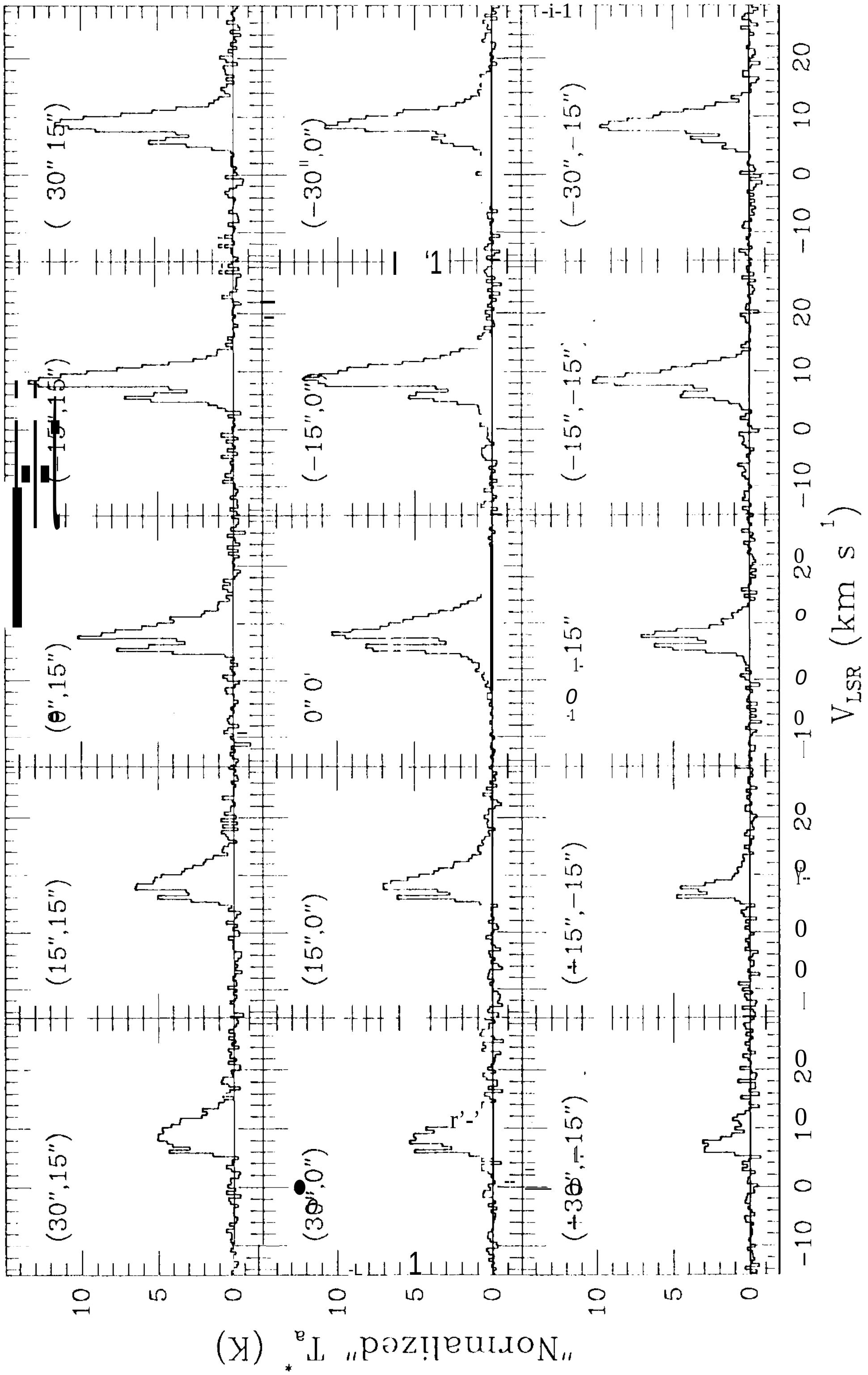

Fig. 2.— CO J=3-2 spectra. Offsets from the (0,0) position (at (B1950) $4^h28^m50.5^s$, -11 18°02′ lo’”) are indicated for each spectrum.

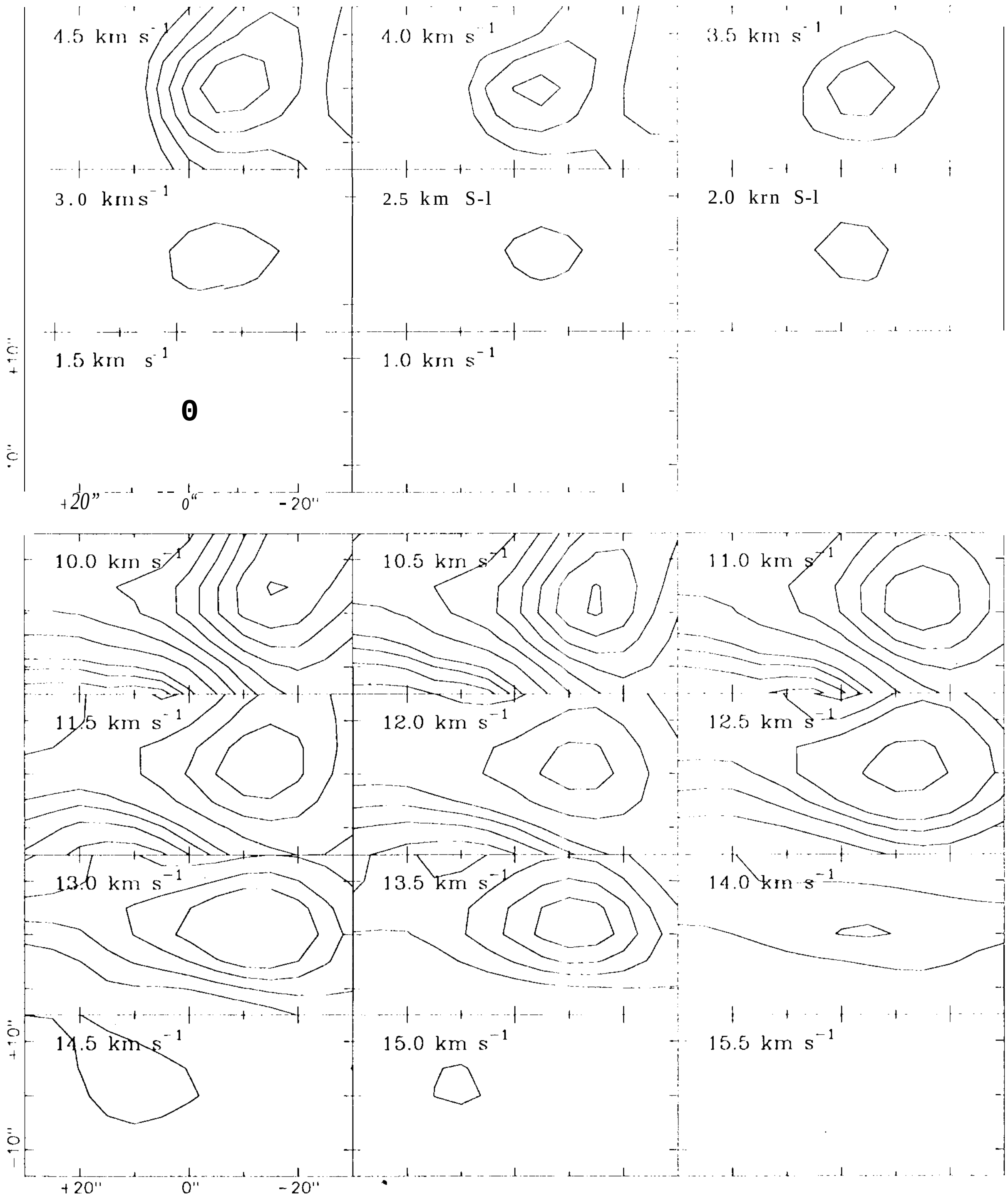

Fig. 3--- Channel maps showing blue-shifted emission (above), and red-shifted emission (below), in 0.5 km s^{-1} intervals. Offsets are in arcsec from the position of L1551NE. The velocity interval from 4.5 to 10.0 km s^{-1} has been omitted because of confusion due to self-absorption and probable contamination from the IRS5 outflow.